DECLINING ROOT STRENGTH IN DOUGLAS-FIR AFTER FELLING AS A FACTOR IN SLOPE STABILITY

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CONTENTS

ABSTRACT

Numbers of roots present per unit area of soil and the individual root tensile strength for two varieties of Douglas-fir--Coast fir (Psuedotsuga menziesii) in western Oregon and Rocky Mountain fir (var. glauca) in central Idaho decreased rapidly with time after felling. Seventy-five percent of the Douglas-fir roots 1 cm or smaller in diameter were lost within 24 months after felling in the coastal variety, and within 60 months after felling in the Rocky Mountain variety.

Numbers of roots per unit area of soil were combined with tensile strength of individual roots to estimate total tensile strength per unit area of soil. Total tensile strength declined from about 1,700 kg/m^2 to about 230 kg/m^2 within the first 30 months after felling for roots 1 cm and smaller of the Coast Douglas-fir. Total tensile strength declined from about 850 kg/m^2 to about 300 kg/m^2 for the same time period and root size class of the Rocky Mountain Douglas-fir. Coast Douglas-fir roots are stronger than those of the Rocky Mountain variety, but decay faster. Live strength is a characteristic of the variety of fir, but differences in decay rates are probably a function of climate.

INTRODUCTION

The role of tree root strength in the stability of slopes has been the subject of speculation and experimentation for several years. There is an increasing need to understand the effect of tree root strength on slope stability wherever land with a high potential for slope failure provides valuable timber and water resources. Land managers must have quantitative data on the effects of timber removal upon slope stability to make decisions as to where, how much, and by what method timber may be safely harvested from areas where landslides are common.

This study originated as a result of the concern by the Bureau of Land Management (BLM) in western Oregon over timber harvesting on shallow soils having a high potential for landslides. The lands support old-growth timber stands of up to 80,000 board feet per acre, with Coast Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) the principal commercial species. In addition, all of the larger streams support anadromous fish. The primary objective of the BLM field study was to identify areas with a high potential for slope failure by debris avalanches and flows by measuring the five major stability factors: slope gradient, soil depth, pore water pressure, soil shear strength, and root strength. A secondary objective was to determine how many trees could be safely removed from certain sites without causing slope failures through loss of root strength.

The study was initially limited to certain portions of western Oregon. However, in other parts of the Rocky Mountains where debris avalanches and flows are also common, Douglas-fir root systems may also influence slope stability. The question then arose whether the roots of the Rocky Mountain variety of Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco) were as strong as the coastal variety. Therefore, the study of Douglas-fir root systems was expanded to include the root strength of Douglas-fir in the mountains of central Idaho.

This report describes and compares the decrease in numbers of roots and the decline in tensile strength of individual roots with time after felling, for two varieties of Douglas-fir. These data are then combined to describe the decline of root strength in terms of force per unit area. Finally, results are compared against observations of unstable slopes, and the role of roots in slope stability is discussed.

Work in progress is aimed at developing and testing criteria and equations for applying root strength in analyses of slope stability. This work will be the subject of future reports.

STUDY AREAS

That portion of western Oregon judged to have a high frequency of debris avalanches and flows contains about 606,036 hectares (2,340 square miles). This area is underlain by the Tyee and Yamhill Formations (Wells and Peck 1961) as shown in figure 1. Much of the western portion of these lands is composed of steep, highly dissected slopes, with shallow, loamy-skeletal soils. A heavy winter rainfall interacts with these factors to create a high potential for debris avalanches and debris flows.

Figure 1. The western Oregon study area (adapted from Wells and Peck 1961). Shading indicates lands with high potential for debris avalanches and flows.

The geologic material is mainly sandstone of the Tyee Formation described (Wells and Peck 1961) as:

> ...rhythmically bedded feldspathic and micaceous massive-bedded sandstone and subordinate siltstone.... Each bed is graded, ranging from coarse sandstone at the base to fine sandstone and siltstone above...

The Yamhill Formation is similar to the underlying Tyee Formation, with massive-bedded sandstone and siltstone and shale interbeds. The relatively hard sandstone of both formations may form cliffs, and also may form slopes from 65 to more than 120 percent leading away from concave headwalls on narrow ridges. The underlying sandstone may be hard and relatively smooth and massive, or it may be well fractured. Thick beds of siltstone form more moderate slopes of 45 to 70 percent.

Soils range in depth from less than 25 cm (10 in) over hard sandstone to 4 m (13 ft) in deep colluvial deposits in channel bottoms and in pockets where the bedrock is deeply weathered. Table 1 lists some characteristics of the soil series commonly found in the most slide-prone portions of western Oregon, as described by Townsend and others (in press).

Table 1.--*Some characteristics of soils common to the Oregon and Idaho study areas*

Soil types or land types	Coarse fragment content	Depth to bedrock	Underlying geologic material
	(% by vol.)		
		OREGON	
Umpcoos Very gravelly sandy loam	> 35	25 to 50 cm	Hard, massive, sandstone
Jason Gravelly loam	> 35	25 to 50 cm	Soft or fractured sandstone and siltstone
Digger Gravelly loam	> 35	0.5 to 1.0 m	Sandstone and siltstone
Bohannon Gravelly clay loam	< 35	0.5 to 1.0 m	Sandstone and siltstone
Slickrock Gravelly loam	< 35	1.0 to 1.5 m	Weathered sandstone or siltstone
		IDAHO	
F4 Loams	variable	25 cm to 1 m	Weathered granite
F5 Sandy loams	variable	25 cm to 1 m	Hard to well-weathered, massive granite

The Idaho study site was located on the Boise National Forest along the South Fork of the Payette River near Lowman in the southern part of the Idaho Batholith (fig.2). This part of the Batholith is made up of a granodiorite, that may range from massive, practically unweathered rock to a highly fractured, highly weathered material. Soil also varies with depth ranging from 50 cm to 1 m (table 1). Soil textures are generally coarse and single-grained, with a clay plus silt content of from 5 to 15 percent (Megahan 1969).

Figure 2.--The central Idaho study area (adapted from Ross and Forrester 1959). Shading indicates lands with high potential for debris avalanches and flows.

Most of the precipitation in the southern Batholith occurs as snow, which reaches maximum accumulation between March 1 and April 15. Large, long-duration Pacific storms may occur in the winter, and these storms often cause flooding as a result of rain and accelerated snowmelt. Mass erosion in the Idaho Batholith is most often the result of rain or rain-augmented snowmelt from October 15 to April 15 (Megahan 1969). For example, a survey of just one district of the Payette National Forest, following intense rain and snow in December 1964, showed more than 400 mass failures. A large natural burn of about 600 acres that occurred 3 to 4 years before was the source of 45 percent of these failures, while undisturbed forest had only 5 percent. Stream channels suffered 30 percent, and roads 20 percent of the total number of failures (Megahan 1969). The relatively high percentage of mass failures that occurred on the burned-over area indicates that declining root strength following death of trees may be an important factor in mass failure of shallow soils on steep slopes in the Idaho Batholith.

The F4 and F5 land types contain major habitat types in the Douglas-fir series, with minor habitat types in the ponderosa pine and subalpine fir series. Samples for measuring characteristics of root systems were taken from the Douglas-fir/ninebark (*Pseudotsuga menziessi* var. *glauca-Physocarpus malvaceus*) habitat type. Both land types are rated as having high mass failure potential (Wendt and others 1975).

OTHER STUDIES RELATING TREE ROOTS TO SLOPE STABILITY

Investigators have recognized the correlation between timber cutting and increased frequency of landslides with time after logging. Most notable was the paper by Bishop and Stevens (1964), who wrote that the number and acreage of slides in southeast Alaska increased more than 4.5 times within 10 years after logging. They attributed the increasing frequency of landslides following logging to root deterioration, which requires several years to exert its full impact on slope stability.

Nakano (1971), reporting on the results of research in Japan, showed that the resistance of stumps to uprooting decreased with years after cutting. The decreasing root strength on a unit area basis was offset by increasing resistance to uprooting of the young trees growing on the site. The net result of timber cutting was an increasing frequency of landslides, expressed as a percentage of land area, until about 16 years after cutting. From there on, the increasing root strength of the young growing stand reduced the frequency of landslides to the preharvest level.

Actual measurements of the decrease in tree root strength following cutting are not commonly found in the literature. Swanston (1969) mentions that Alaskan measurements of shear strength perpendicular to the grain of lateral roots greater than 1 inch in diameter showed a very gradual decrease in strength with time after cutting. Decay was not evident in roots from stumps less than 4 years old, but was almost always found in roots from stumps older than 4 years.

O'Loughlin (1974) studied landslides in southern British Columbia and found that a high percentage of roots of all sizes along the margins of landslides failed in tension, while a smaller percentage failed in shear. O'Loughlin's work was concerned mainly with determining the rate at which the tensile strength of Douglas-fir and western redcedar roots decreased with time after cutting. His results showed that the tensile strength of Douglas-fir roots decreased by more than one-half within 3 years after cutting. Cedar roots required 5 years to lose one-half of their tensile strength. O'Loughlin's data did not include changes in the numbers of roots by size classes with years after cutting. He alluded to this phenomenon by mentioning "...that the roots taken from older stumps were larger than roots sampled from younger stumps..." He noted that old cedar stumps in an area clearcut in the 1930's retained roots with diameters greater than about 15 cm, and that the smaller roots had decayed and disappeared probably years before. He also measured the diameters of 150 broken roots from the soil below 45 cm in the headscarps of three landslides. The mean of these diameters (whether inside or outside bark was not stated) was 1.07 cm. He concludes that "small roots constitute a major part of the root network in the lower B horizon of the stony mountain soils." This points out that it is important to measure the change in the numbers of roots, particularly the smaller sizes, with time after cutting as well as to measure the declining tensile strength of roots.

The question remains as to how to apply quantitative data to equations used in analyzing slope stability once the decay function of root systems is understood. A Japanese study (Endo and Tsuruta 1969) measured the increase in soil shear strength by making large-scale direct shear tests on soil pedestals containing live tree roots. The soil shear strength increased directly with the bulk weight of roots per unit volume of soil. Their results showed that data on the shear strength of soil with live roots fit the equation, $S = \alpha + \beta R + \sigma \tan \phi$; where

S = total shear strength in kg/m^2
α and β = empirical constants
R = weight of roots in g/m^3
σ = normal stress in kg/m^2
ϕ = angle of internal friction of the soil.

Note that tree root strength is considered to be a cohesive force. Swanston (1970) made a stability analysis of three landslides in cohesionless soils in southeastern Alaska and found that an "apparent cohesion" of 69 to 89 pounds per square foot was needed to maintain stability. He concluded that the most likely source for this stabilizing force was the anchoring effect of tree roots growing through the slide-prone, weathered till into the compacted till. Swanston and Dyrness (1973) considered roots to "provide continuous long-fiber cohesive binders to the soil mass proper and across local zones of weakness within the soil mass." In their opinion, the anchoring effect of roots can be extremely important on some steep, shallow soils of the western United States.

STUDY METHODS

Samples of tree roots were taken from locations within old-growth (100 to 200 years), Douglas-fir sites in uncut stands and unburned cutover areas. The ages of the cutover areas ranged from 2 to 111 months for the Oregon sites, and 2 to 144 months for the Idaho sites. The ages of cutover areas were determined by consulting records, foresters, and contract administrators. One representative tree or stump in each location was selected as the center of a plot. The slope gradient of the site and the location and diameters of all neighboring trees or stumps were measured by tape, abney level, and compass. A pit for root sampling was located halfway between the center of the plot and one of the neighboring trees or stumps. Criteria for the location of a pit were: trees or stumps were to be Douglas-fir; avoid patches of woody shrubs such as vine maple (*Acer circinnatum*); and avoid immovable piles of logging debris.

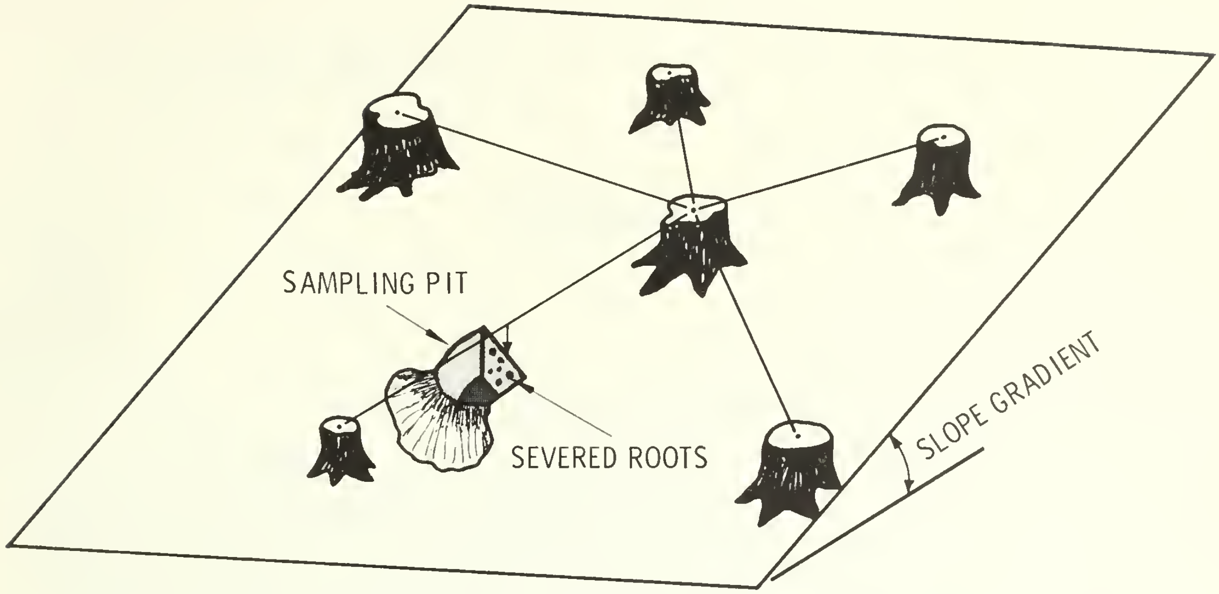

Figure 3.--Central stump of sampling site connected to neighboring stumps by rays.

Each pit was dug 1 m wide and to a depth of 1 m or to bedrock, whichever was shallower. The face of the pit was located at the center of and at right angles to the ray connecting the center of the plot and the neighboring tree or stump (fig. 3). Root samples for testing of tensile strength were collected as the pit was excavated. Living Douglas-fir roots of both varieties have a distinctive, crimson-colored inner bark, which made them easy to identify. The bright color darkened to a brownish red in dead Douglas-fir roots, which was still distinctive. The diameter, inside bark, of each Douglas-fir root found in the pit face was measured and recorded. The sizes of these roots ranged from 0.4 mm (0.016 in) up to about 10 cm (4 in). Root samples were stored temporarily in a 50 percent solution of isopropyl alcohol until they could be transported to the lab and stored in a solution of eight parts alcohol and one part formaldehyde. The alcohol-formaldehyde solution was used to kill any micro-organisms that could continue the decay of roots during storage.

A device was designed and constructed to measure the tensile strength of tree roots, using hydraulic pressure to hold the ends of the sample.[1] Another hydraulic cylinder applied a tensile force to cause failure, and a dynamometer measured the tensile force at failure. Roots up to 14.3 mm (0.56 in) in diameter could be tested. The capacity of the device was limited only by the holding ability of the hydraulically operated grippers and the 1,000-lb capacity of the dynamometer. The tensile tests were not strain controlled. Each root (saturated from the alcohol-formaldehyde solution) had the bark carefully stripped, the ends secured in the tensile tester, and tensile force applied. The maximum tensile force at failure was recorded by the "lazy hand" on the dynamometer. The average diameter of the root at the break was measured and recorded along with any notes on obvious decay, high resin content, and bends or crooks which may have affected the tensile strength. All roots were tested as long as the ends of the sample were straight enough to fit in the tester and the sample was not too decayed to prepare for testing. More than 90 percent of the roots broke outside of the end clamps. Test results for those roots which failed within the end clamps were discarded.

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[1]The authors are indebted to Bland Z. Richardson of the Forest Service, Intermountain Forest and Range Experiment Station, for designing and supervising the construction of this instrument. A publication describing this device in detail is in preparation.

RESULTS

Numbers of Roots Per Unit Area of Soil

Analysis of measurements of the numbers of roots present in the soil with time after felling of the stand showed distinct differences between Coast and Rocky Mountain Douglas-fir. Plots of these data showed that the decline in numbers of Coast Douglas-fir roots followed a distinctive curve--concave upwards with a steeply climbing left limb and a gradually declining right limb. The curve expressing the prediction equation, as shown in figure 4, was developed using the techniques of Jensen and Homeyer (1970) and Jensen (1973). The appendix presents curves fitted to raw data.

The Rocky Mountain Douglas-fir showed a less rapid decline in numbers with time according to the semilogarithmic model: $N = a + b \log_{10} (\text{Time} + 1)$. The constant 1 was added to the time after felling in months to allow the logarithmic transformation of data from live roots, where the time after felling is zero. Figure 5 shows the predicted numbers of roots with time after felling; figure 6 presents the parameters and equations for both varieties of Douglas-fir. (Curves are fitted to raw data in the appendix.)

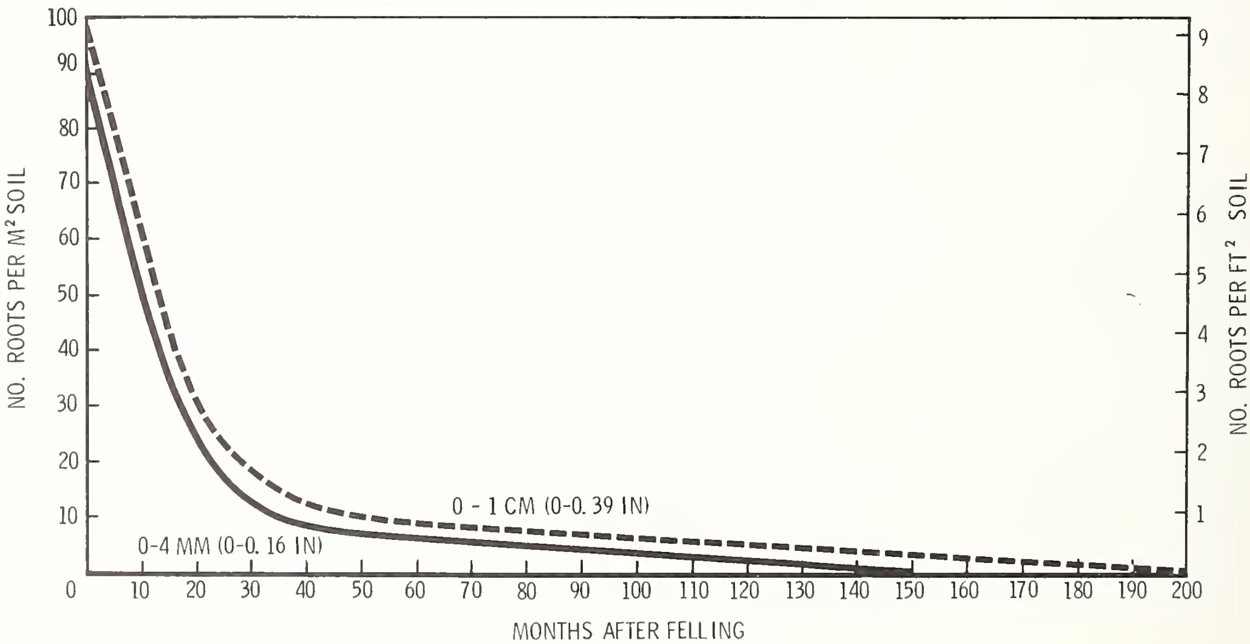

Figure 4.--Decline in numbers of Coast Douglas-fir roots per unit area of soil.

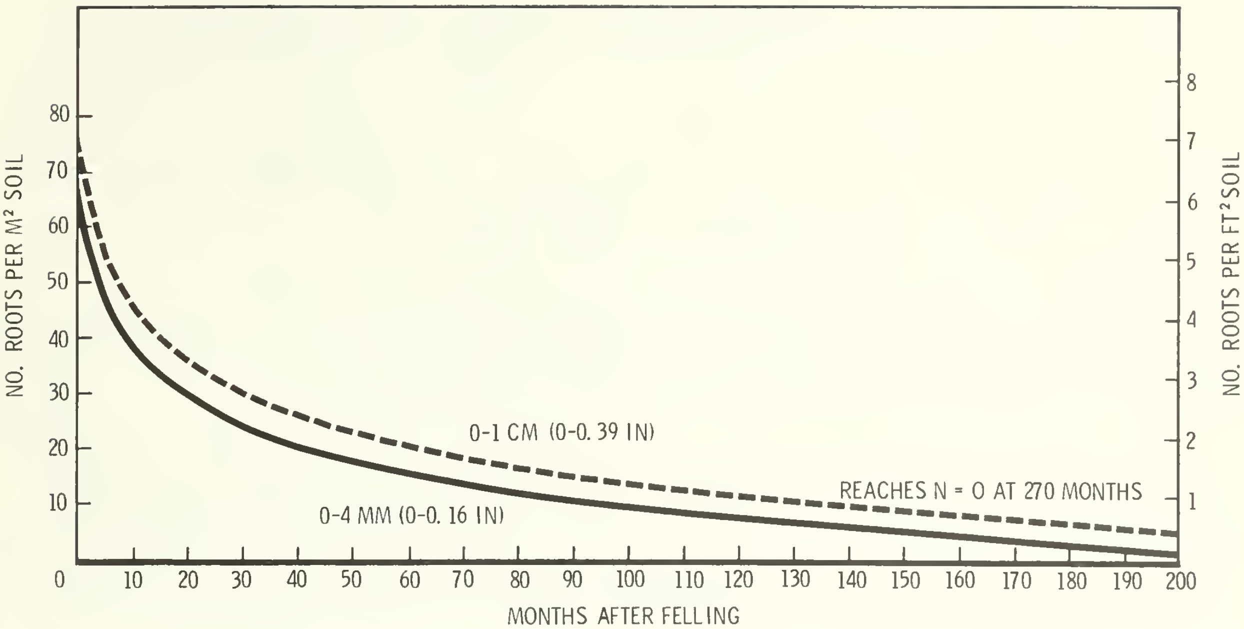

Figure 5.--Decline in numbers of Rocky Mountain Douglas-fir roots per unit area of soil.

Coast Douglas-fir: $N = a \cdot e^{-\left|\frac{\frac{b - \text{Time}}{c} - 1}{d}\right|^{f}} + (1 - \frac{\text{Time}}{b})\, g$

where: N = numbers of roots per unit area of soil; Time = months following felling (live roots have time = 0); range = 0 to 111 months.

Units	Diameter size class	a	b	c	d	f	g	r^2	Sy·x	F[1/]	Mean N	Mean time
N/m^2	0 to 4 mm	247.4	150	250	0.39	5	10.9	0.86	13.03	184	29.9	36.6
N/f^2	0 to 0.16 in	23.0	150	250	0.39	5	1.01	0.86	1.21	184	2.8	36.6
N/m^2	0 to 10 mm	232.2	200	250	0.20	2.7	12.9	0.89	11.66	259	34.5	36.6
N/f^2	0 to 0.39 in	21.6	200	250	0.20	2.7	1.20	0.89	1.08	259	3.2	36.6

Rocky Mountain Douglas-fir: $N = a + b \log_{10} (\text{Time} + 1)$

where: N = numbers of roots per unit area of soil; Time = months following felling (live roots have time = 0); range = 0 to 144 months.

Units	Diameter size class	a	b	r^2	Sy·x	Sa	Sb	F[1/]	Mean N	Mean time
N/m^2	0 to 4 mm	69.2	-30.0	0.96	5.20	2.77	1.71	298	26.4	54.6
N/f^2	0 to 0.16 in	6.4	- 2.8	0.96	0.48	0.26	0.16	298	2.5	54.6
N/m^2	0 to 10 mm	77.2	-31.7	0.93	6.90	3.68	2.27	194	32.0	54.6
N/f^2	0 to 0.39 in	7.2	- 2.9	0.93	0.64	0.34	0.21	194	2.9	54.6

[1/] All F values are highly significant at the 99 percent level.

Figure 6.--Statistics and equations for estimating the numbers of roots per unit area of soil with time after felling for Coast and Rocky Mountain Douglas-fir.

Time after felling was the only independent variable used in this analysis. Information on tree spacing and tree diameter is expected to affect the numbers of roots per unit area of soil, but these data will be reserved for future analyses.

Figures 4 and 5 show that the Coast Douglas-fir has a greater number of live roots per square meter of soil in all size classes and has a faster decline in numbers with time after felling than the Rocky Mountain Douglas-fir. It can be seen that the Rocky Mountain Douglas-fir roots in a given size class remain intact about 35 percent longer than Coast Douglas-fir roots when the curves are extended to the horizontal axis of figures 4 and 5. These estimations of the time required for the numbers of roots 0 to 1 cm in diameter to reach zero is a minor extrapolation from the data for Coast Douglas-fir and a major extrapolation for the Rocky Mountain variety. It is speculative how much of this difference in durability is caused by differences in the wood and how much is caused by differences in climate and the activity of micro-organisms.

The remaining roots larger than 1 cm (0.39 inch) were subdivided into size classes and analyzed to see if there was a trend in numbers with time by comparing the slope of a regression line for each class with zero. We would expect that the numbers of these roots would eventually reach zero. However, the results of these tests showed that the numbers of roots in the larger size classes remained constant with time over the range in time used in this study. Table 2 presents the mean value of the number of roots per unit area of soil for each size class and the mean diameter of the roots in each size class.

Table 2.--*Mean numbers of Coast and Rocky Mountain Douglas-fir roots per unit area of soil for the larger size classes*

Size class	Mean diameter	Number/meter^2	Number/foot^2
	COAST DOUGLAS-FIR		
1 to 2 cm	1.46 cm	1.59	--
0.39 to 0.78 in	.72 in	--	0.147
2.1 to 4 cm	2.78 cm	.409	--
0.79 to 1.59 in	.90 in	--	.0380
4.1 to 6 cm	4.54 cm	.106	--
1.60 to 2.38 in	2.23 in	--	.00987
6.1 to 8 cm	6.46 cm	.104	--
2.39 to 3.17 in	2.67 in	--	.00971
	ROCKY MOUNTAIN DOUGLAS-FIR		
1 to 2 cm	1.36 cm	1.92	--
0.39 to 0.78 in	.68 in	--	.178
2.1 to 4 cm	2.86 cm	.922	--
0.79 to 1.59 in	1.36 in	--	.0857
4.1 to 6 cm	5.15 cm	.111	--
1.60 to 2.38 in	2.00 in	--	.0103
6.1 to 8 cm	6.39 cm	.0584	--
2.39 to 3.17 in	2.52 in	--	.00543

The greatest source of error in the data on the decline in numbers of roots with time is the determination of the correct date of felling. Errors in dating the cut have their greatest effect on samples from the younger clear-felled areas because of the rapid initial decline in numbers. Fortunately, the younger cuts are the easiest to date accurately because of the availability of records and personnel who administered the sale. An error in dating of as much as 6 months would have relatively little effect on root samples from an area cut 10 years ago.

Tensile Strength of Individual Roots

Tensile strength of roots was plotted against diameter (inside bark) by time after felling, and these results showed distinct differences in the rate of decline of strength with time after felling for the two varieties of Douglas-fir. The model for root tensile strength was nonlinear for each variety, with strength a function of diameter raised to an exponent which is a function of time after felling. The models and their statistics are shown in figure 7.

Figure 8 shows that predicted root tensile strength of Coast Douglas-fir for various times after felling. The strength of a 1 cm root drops from 341 to 175 kg at 12 months after felling--a loss of 49 percent in 1 year. By 48 months after felling, a 1 cm root has lost 74 percent of its live strength.

COAST DOUGLAS-FIR

$$\text{Tensile Strength} = a\,(b\cdot\text{Diameter})^{(1.8\,-\,0.06\sqrt{\text{Time}})}$$

where: Time = months after felling (live roots have time = 0).

Strength units	Diameter units	a	b	r^2	$Sy\cdot x$	F[1/]
Kilograms	Millimeters	1.04	2.516	0.804	19.2	885
Pounds	Inches	2.30	0.0156	0.804	42.3	885

ROCKY MOUNTAIN DOUGLAS-FIR

$$\text{Tensile Strength} = (a - b\cdot\text{Time})\,(c\cdot\text{Diameter})^{(1.676\,-\,0.0004\cdot\text{Time})}$$

where: Time = months after felling (live roots have time = 0).

Strength units	Diameter units	a	b	c	r^2	$Sy\cdot x$	F[1/]
Kilograms	Millimeters	180.2	0.381	0.0786	0.802	20.4	456
Pounds	Inches	397.3	0.840	0.000489	0.802	44.9	456

[1/] All F values are highly significant at the 99 percent level.

Figure 7.--Models for individual root tensile strength for two varieties of Douglas-fir.

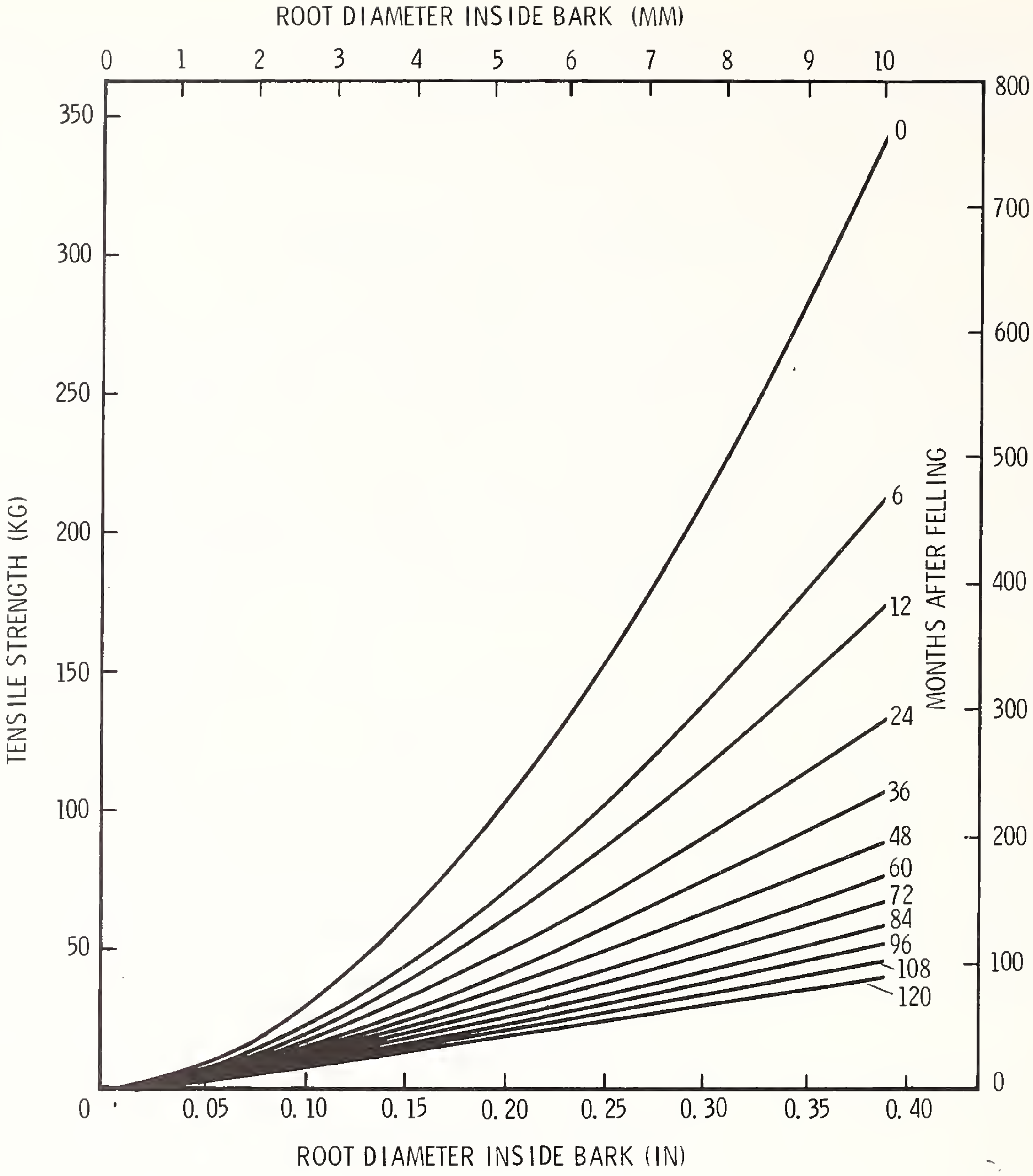

Figure 8.--Individual root tensile strength for Coast Douglas-fir.

The Rocky Mountain variety proved to have relatively weak roots with a slow, gradual decline in strength with time after felling. Figure 9 shows the predicted root tensile strength by diameter and time after felling (note the change in scale from fig. 8 to fig. 9). A 1 cm root loses only 30 percent of its fresh tensile strength after 144 months.

A comparison of these two figures illustrates the difference in root strength and its decline with time after felling for the two varieties of Douglas-fir. A 1 cm root of Rocky Mountain Douglas-fir has only 35 percent of the strength of Coast Douglas-fir when fresh, but is about 2.2 times as strong after 120 months.

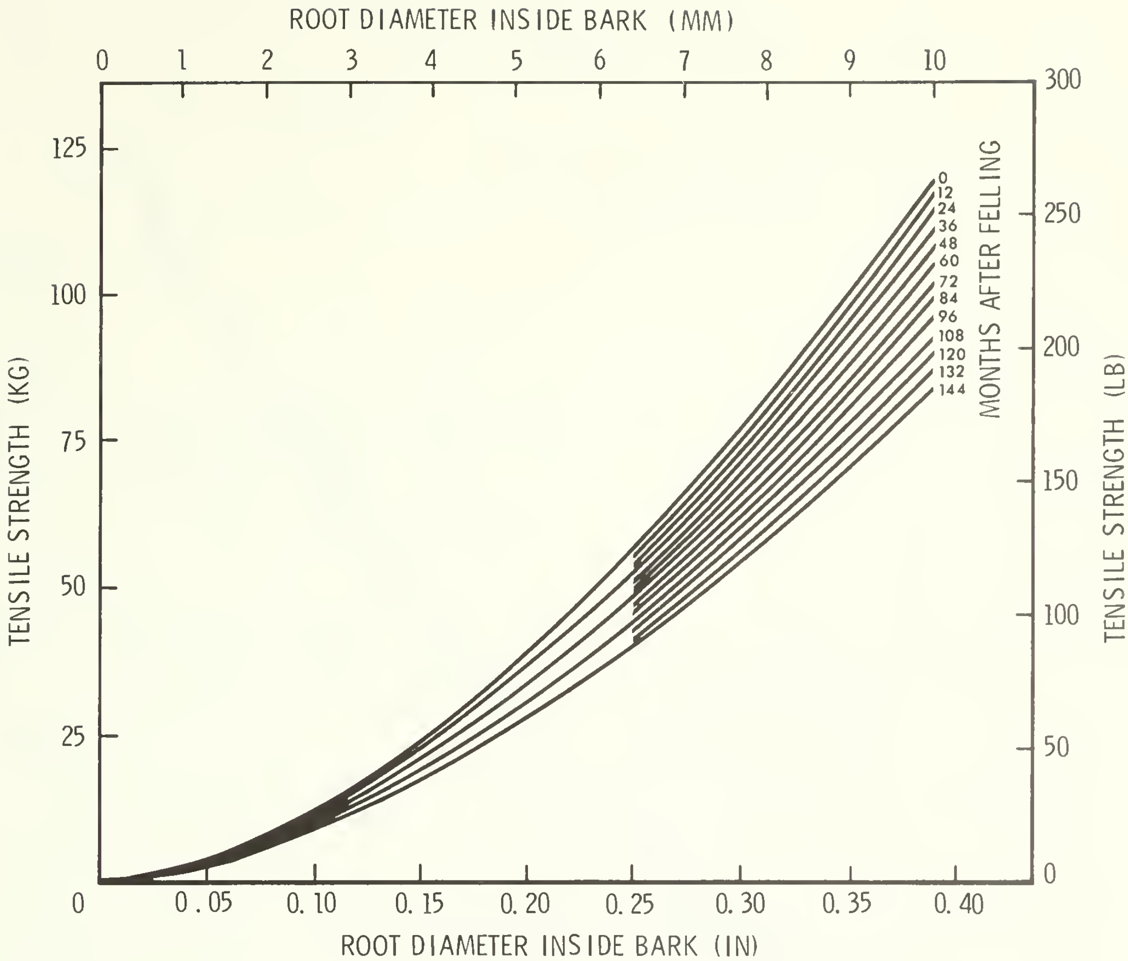

Figure 9.--Individual root tensile strength for Rocky Mountain Douglas-fir.

The prediction equation for Coast Douglas-fir (fig. 7) was applied to the results of laboratory tensile tests on Coast Douglas-fir from British Columbia in a publication by O'Loughlin (1974). Figure 10 shows O'Loughlin's plotted data for live roots, with the predicted curve from this study superimposed. The relatively good fit of this curve indicates that the tensile strength of live Coast Douglas-fir roots does not vary from Oregon to British Columbia.

O'Loughlin's data show much less scatter than data developed during this study. O'Loughlin selected straight, uniform sections of roots for his laboratory tests, which reduces the variance of the test results. In the present study, all roots were tested regardless of crooks, resinous portions, or advanced decay. This increases the variance of the results, but it also gives an estimate of the variation that may be expected in the natural populations.

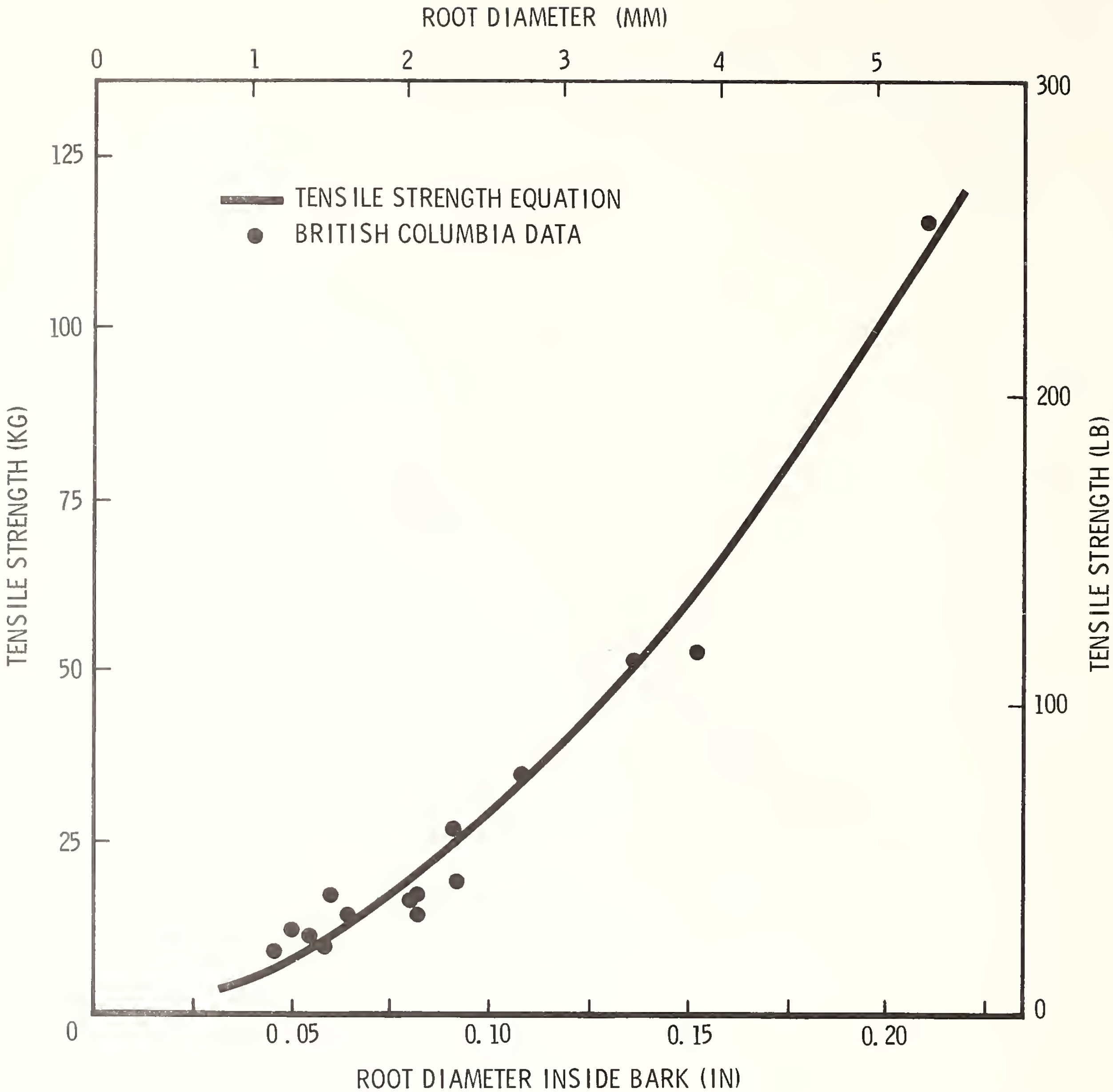

Figure 10.--Application of the tensile strength equation to British Columbia data for live roots.

Root Tensile Strength Per Unit Area of Soil

The next step in the analysis was to combine the numbers of roots per unit area of soil and the individual root tensile strengths to estimate the total root tensile strength per unit area of soil. This was done by summing the product of the number of roots of each diameter in a sample pit and the estimated tensile strength for each diameter. This process formed a data set of tensile root strength per unit area of soil based on samples from live stands and from areas felled up to 144 months before. It should be emphasized that these data represent the maximum root tensile strength per unit area of soil in a vertical plane oriented as a perpendicular bisector to a ray connecting two trees or stumps (fig. 3).

General Model: $\dfrac{\text{Tensile Strength}}{\text{Unit Area of Soil}} = a \cdot e^{-\left|\dfrac{\frac{b - \text{Time}}{c} - 1}{d}\right|^{f}} + (b - \text{Time})\, g$

where: Time = months after felling (live sites have time = 0).

Strength units	Root size class	a	b	c	d	f	g	r^2	Sy·x[1/]	F[1/]
				COAST DOUGLAS-FIR						
Kg/m^2	0 to 1 cm	2840	200	300	0.36	6.0	1.02	0.826	229.6	71.3
$\#/ft^2$	0 to 0.39 in	592.0	200	300	.36	6.0	.208	.826	47.05	71.3
Kg/m^2	0 to 4 mm	1435	120	300	.60	7.0	1.59	.913	77.0	156.9
$\#/ft^2$	0 to 0.16 in	294.1	120	300	.60	7.0	.326	.913	15.8	156.9
				ROCKY MOUNTAIN DOUGLAS-FIR						
Kg/m^2	0 to 1 cm	1134	430	475	.10	5.0	.770	.709	112.2	19.6
$\#/ft^2$	0 to 0.39 in	232.3	430	475	.10	5.0	.158	.709	23.0	19.6
Kg/m^2	0 to 4 mm	322.1	155	180	.15	3.5	1.012	.836	42.8	76.3
$\#/ft^2$	0 to 0.16 in	65.98	155	180	.15	3.5	.207	.836	8.77	76.3

[1/] The distribution will be assumed to be normal until otherwise established. The propriety of the Sy·x and F estimators is contingent upon this assumption.

Figure 11.--Models for predicting total root tensile strength per unit area of soil by time after felling. (Total root strength per unit area of soil was developed using actual numbers of roots per unit area and the estimated individual root tensile strength.)

One-half of the data for each variety of Douglas-fir were selected at random and used to develop the curve form for the decline in tensile strength with time after felling, while the remaining data were used to test the accuracy of the curve fitted to each set of data. The models and their statistics are shown in figure 11. The appendix presents plots of the raw data and the fitted curves.

Figure 12 shows the decline in total root tensile strength per unit area of soil for Coast Douglas-fir for two size classes; figure 13 provides this information for the Rocky Mountain variety. Plots of the data reserved for curve-form development indicated that the form of the relationship would be reasonably approximated by a combination of a concave upward curve sloping steeply to the left and a linear segment sloping gently to the right. These curves were fitted by the methods outlined by Jensen (1973).

Time after felling was the only independent variable used in this analysis. Tree spacing and tree size is expected to affect the numbers of roots per unit area of soil and thereby also affect the tensile strength per unit area of soil. These data have been reserved for future analyses.

A comparison of figures 12 and 13 shows that for the 0 to 1 cm size class, the Coast Douglas-fir at time zero has nearly twice the strength of the Rocky Mountain Douglas-fir. The strength values are about equal 30 months after felling, and by 144 months, the Rocky Mountain Douglas-fir has about 3.6 times the strength per unit area of soil as the Coast Douglas-fir.

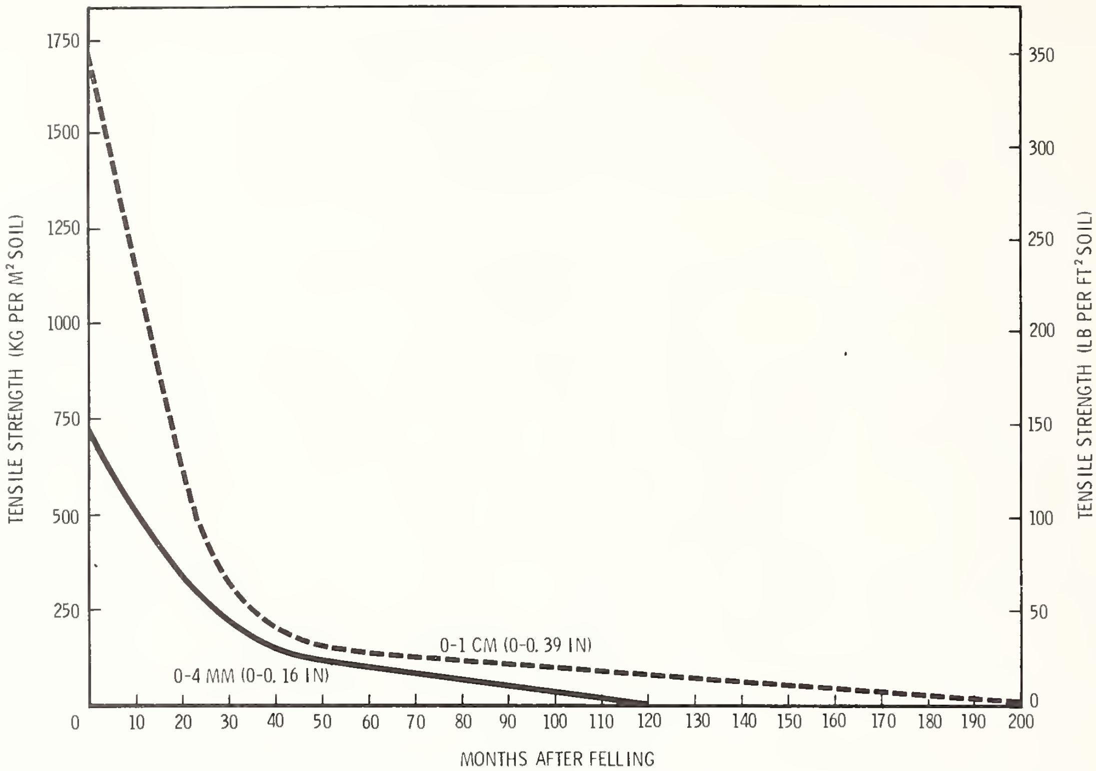

Figure 12.--Root tensile strength per unit area of soil for Coast Douglas-fir.

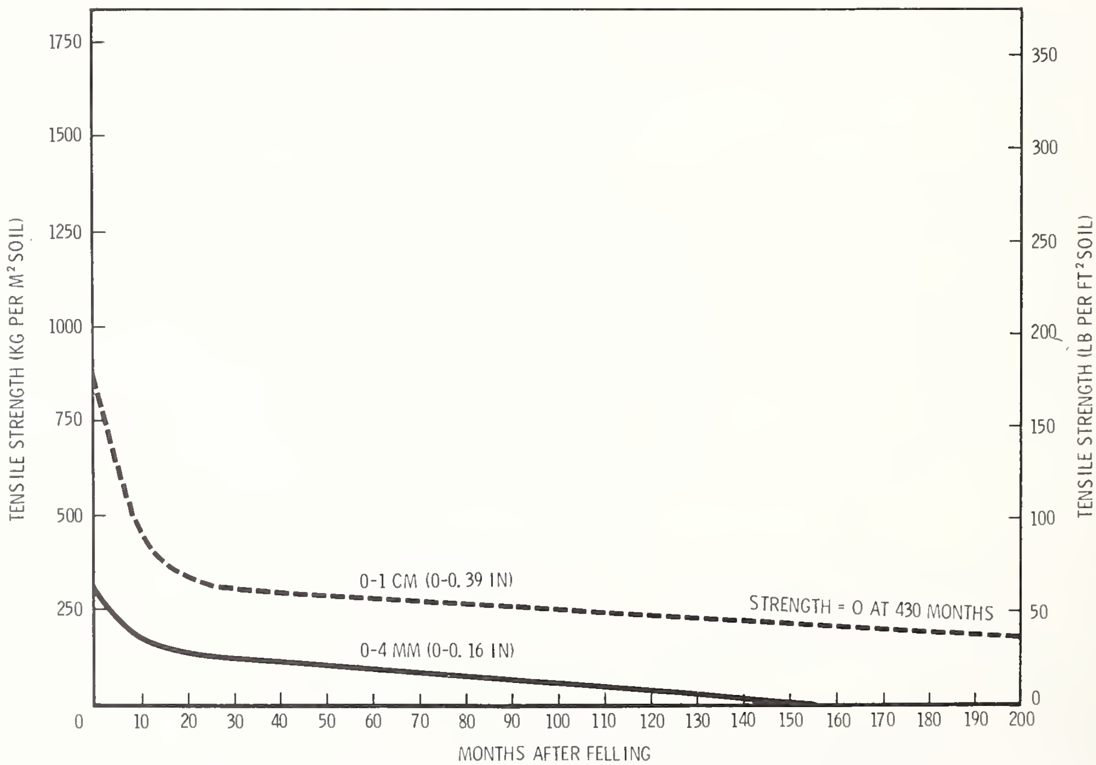

Figure 13.--Root tensile strength per unit area of soil for Rocky Mountain Douglas-fir.

DISCUSSION

From the observations and measurements made during this study, a concept was developed to explain how the change in numbers and strength of tree roots after felling affects slope stability. The presence of Douglas-fir roots in pits dug halfway between trees in living stands supports the idea that living tree roots form a reinforcing network in the soil. The finer roots (1 cm and smaller) are found throughout the rooting zone of each tree's root system. It is at the lateral edges of the root mass and across the bottom of the root system that the fine roots have their greatest effect on slope stability.

There are three important ways in which these fine roots increase the shear strength of the soil mass. First, these roots provide tensile reinforcement to the soil mass enclosed within the rooting zone of an individual tree. This effect may be observed on windthrown trees where the entire soil-root mass overturns as a single unit. Second, fine roots will penetrate a shallow soil overlying a weathered or well-fractured bedrock or glacial till to anchor the soil-root mass. This directly increases shear strength of the soil mantle on steep slopes. Third, roots around the lateral edges of the root system co-occupy a common soil volume with roots from adjacent root systems. This tends to form a continuous network of roots in the soil within a living stand of trees. This becomes especially important where shallow soils overlie a hard bedrock surface with few fractures or joints. Under these conditions, tree roots increase the stability of slopes mostly by tensile strength of lateral roots.

Researchers have asked whether roots in the zone of soil shear fail in shear or tension. Tree roots will fail in shear if the roots are held rigidly in the soil matrix and the shear zone is very narrow--only a few millimeters wide. Tree roots will fail in tension whenever the shear zone is wide enough to allow roots crossing the shear zone to deflect, elongate, and develop their maximum tensile strength. Live roots 5 to 10 mm in diameter possess enough tensile strength to cause the surrounding soil to yield as these roots deflect across a shear zone, and this encourages the development of maximum root tensile strength.

The authors feel that shear zones are relatively wide in the forest soils studied for this report and that the majority of tree roots fail in tension. There is evidence that the width of these shear zones can range from 7 to 25 cm. Shear zones in this range have been observed on the margins of slope failures that include tree roots and around root masses of windthrown trees on deep soils. Some of these root masses show a rotational mode of failure with broken tree roots extending from the shear surfaces of the soil-root mass. Studies of slope failures in soils over glacial till in Alaska (Wu 1976) indicate that the expected width of soil shear zones will range from 7.5 to 30 cm and that the expected mode of root failure is in tension.

Root decay begins as soon as a tree is felled and affects the smallest roots immediately because of their thinner bark, less resinous wood, and large surface area relative to wood volume. This causes a rapid decline in numbers of fine roots throughout the rooting zone of an individual tree, together with a sharp decrease in the tensile strength of the remaining roots.

Several effects on the stability of steep slopes may be expected as a result of tree felling. The total tensile strength per unit area of fine roots, which help anchor shallow soils to fractured or weathered bedrock or glacial till, will decrease rapidly within 2 or 3 years after felling. This causes a plane of weakness to develop at the soil-bedrock or soil-till interface where slope stability becomes increasingly dependent upon the shear strength of the soil itself.

Tree felling also causes a zone of weakness to develop around the lateral edges of the soil-root mass of each tree, and this zone steadily widens with time. When viewed from above, the root systems of a living stand of Douglas-fir would be analogous to a patchwork quilt of individual root systems joined at their edges by large numbers of fine roots that co-occupy the soil. After felling, these root systems begin to resemble islands as the fine roots in the soil around the lateral edges of the root systems dwindle in numbers and strength. The margins of the root systems continue to retreat leaving only the larger roots in the soil.

Although these larger roots may retain considerable tensile strength with time after felling, the fine roots disappear within a few years. On windthrown trees, the larger roots around the lateral edges of the root mass are composed of long, ropy laterals, 1 to 2 cm in diameter and larger. The ends of the laterals divide into smaller branches, each with fans of fine roots firmly connected to the soil. Other short, fine roots branch directly from the laterals at intervals along their length. The fine roots decay rapidly after felling and leave the laterals with only a minimal connection to the soil.

The concept of zones of weakness in the soil co-occupied by fine roots from adjacent stumps is illustrated by figures 14 and 15. The road shown in figure 14 was photographed in 1974. Right-of-way timber had been felled during the winter of 1971-72; the slope above the road failed sometime later. The stumps at the upper end of the slope failure are shown close-up in figure 15. The man is standing at the edge of a fissure that has opened in the zone of weakness halfway between the two stumps (arrows). The slope failure has undercut the lower stump and, in this extreme instance,

Figure 14.--Slope failure above a logging road.

Figure 15.--Separation of two stumps at upper end of slope failure.

the soil-root mass with the stump at its center has pulled away from the upper slope. The authors believe that many slope failures in timber harvest areas on steep slopes with shallow soils are initiated by the creation of zones of weakness under and around individual tree stumps, as illustrated in these figures.

The authors conclude that the finer roots (1 cm and smaller) have the greatest effect upon slope stability. It is this size class that is the greatest component of all roots around the periphery of individual tree root systems, and it is this size class that shows the greatest change in numbers and strength with time after felling. Measurements by Bishop and Stevens (1964) in Alaska of the increased frequency of landslides within a few years after timber harvest support this hypothesis.

Other evidence of the connection between the frequency of mass failures and tree felling is shown in an inventory of landslides on a single Ranger District in western Oregon following an intense rainfall period (Gresswell and others 1976). The area included in the inventory contained lands with a high potential for landslides and with Coast Douglas-fir as its principal merchantable timber species. The mass failures were classified as "unit-associated" (clearcut but not related to roads or landings), "road-associated," and "natural" (having no apparent relationship with management activity). The percentages of mass failures associated with each of these three categories were: unit-associated, 77 percent; road-associated, 14 percent; and natural, 9 percent. The 190 mass failures associated with timber harvest areas were subdivided by time after felling as follows: 0 to 3 years after felling--120 failures (65 percent); 4 to 10 years after felling--54 failures (29 percent); and 11 years or more after felling--12 failures (6 percent). The results of this inventory emphasize that the removal of timber from an area with a high potential for slope failure can drastically affect slope stability. Also, the number of mass failures per year in timber harvest areas is greatest within the first 3 years after felling. This corresponds to the period of most rapid decline in both numbers and tensile strength of Coast Douglas-fir roots in the 0 to 1 cm size class as shown in this study.

The values of total root tensile strength per unit area of soil, as shown in figures 12 and 13, represent the maximum root tensile strength and serve as an index of the tensile strength actually available for slope stability. Only a portion of this total root strength will be effective in an actual situation because not all

roots develop their ultimate strength at the same time. When a soil-root mass is at the point of incipient failure, some of the roots have already failed, while others may be at the point of failure, and still others have not yet reached their peak strength.

The authors are developing equations that apply tensile strength per unit area of soil (fig. 12 and 13) to the analysis of slope stability. The equations will be used to estimate the effective tree root strength that acts as an apparent cohesive force and that increases total shear strength of the soil. Following field testing of the equations, results of the work will be reported.

CONCLUSIONS

The results of this study show that the tensile strength of individual fresh roots is distinctive for Coast and Rocky Mountain Douglas-fir. The tensile strength of fresh Coast Douglas-fir roots from Oregon appears to be identical to the strength of fresh Coast Douglas-fir roots from British Columbia. Although stronger than roots of the Rocky Mountain variety when fresh, roots of Coast Douglas-fir lose their strength more rapidly. For example, a fresh Rocky Mountain Douglas-fir root is only 35 percent as strong as a fresh root of the same diameter from a Coast Douglas-fir, but 120 months after felling, a Rocky Mountain Douglas-fir root is 2.2 times as strong as a root from Coast Douglas-fir.

The numbers of roots per unit area of soil also show a sharp decline with time after felling. Rocky Mountain Douglas-fir roots are less numerous than Coast Douglas-fir when live, but are more numerous than Coast Douglas-fir 30 months after felling.

The combination of the numbers of roots per unit area of soil and the tensile strength of individual roots gives the total root tensile strength per unit area of soil. These values decline rapidly with time after felling. Coast Douglas-fir shows a loss of about 82 percent of its strength per unit area of soil within 30 months after felling for roots 1 cm and smaller. By comparison, Rocky Mountain Douglas-fir loses only 64 percent of its total strength in that period of time. By 144 months after felling, Rocky Mountain Douglas-fir has about 3.6 times as much total root strength per unit area of soil as Coast Douglas-fir.

The values of root tensile strength per unit area of soil represent the maximum strength that would be developed if each root arrived at its peak strength at the same time. Tensile strength per unit area, as shown in this paper, may be used as an index of the value of Douglas-fir root strength in slope stability. Equations for calculating slope stability that incorporate the cohesive force of roots, and the field testing of the equations, will be covered in future reports.

The authors conclude that Douglas-fir roots 0 to 1 cm in diameter are the most effective in increasing the stability of timbered slopes. This is based upon the rapid decrease in numbers and tensile strength of roots in this size class with time after felling. These changes match the high frequency of landslides the first few years following timber harvest on slopes with a high potential for failure in western Oregon and central Idaho.

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APPENDIX

Raw Data Plots for Various Size Classes

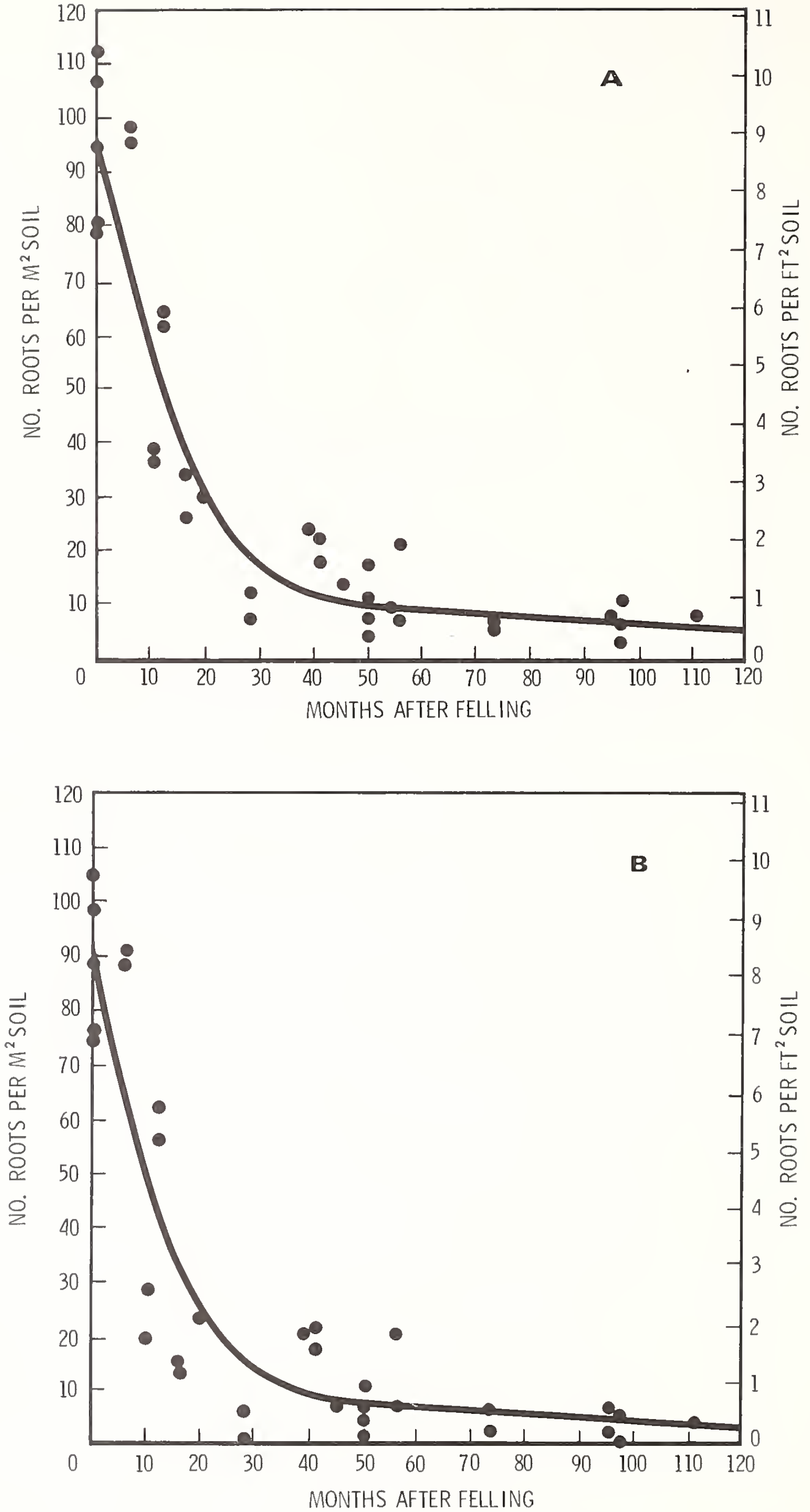
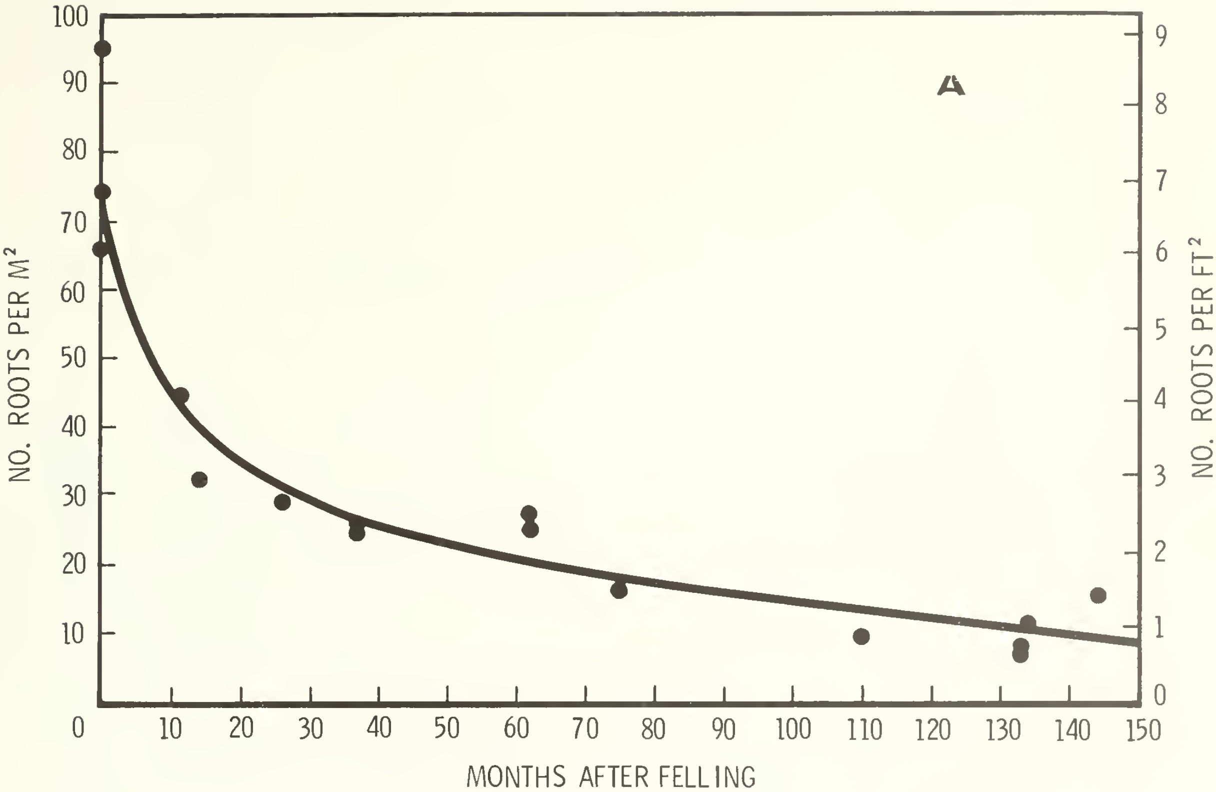


Figure 16.--Decline in numbers of Coast Douglas-fir roots per unit area of soil: A, *Plot of raw data for the 0 to 1 cm (0 to 0.39 in) size class.* B, *Plot of raw data for the 0 to 4 mm (0 to 0.16 in) size class.*



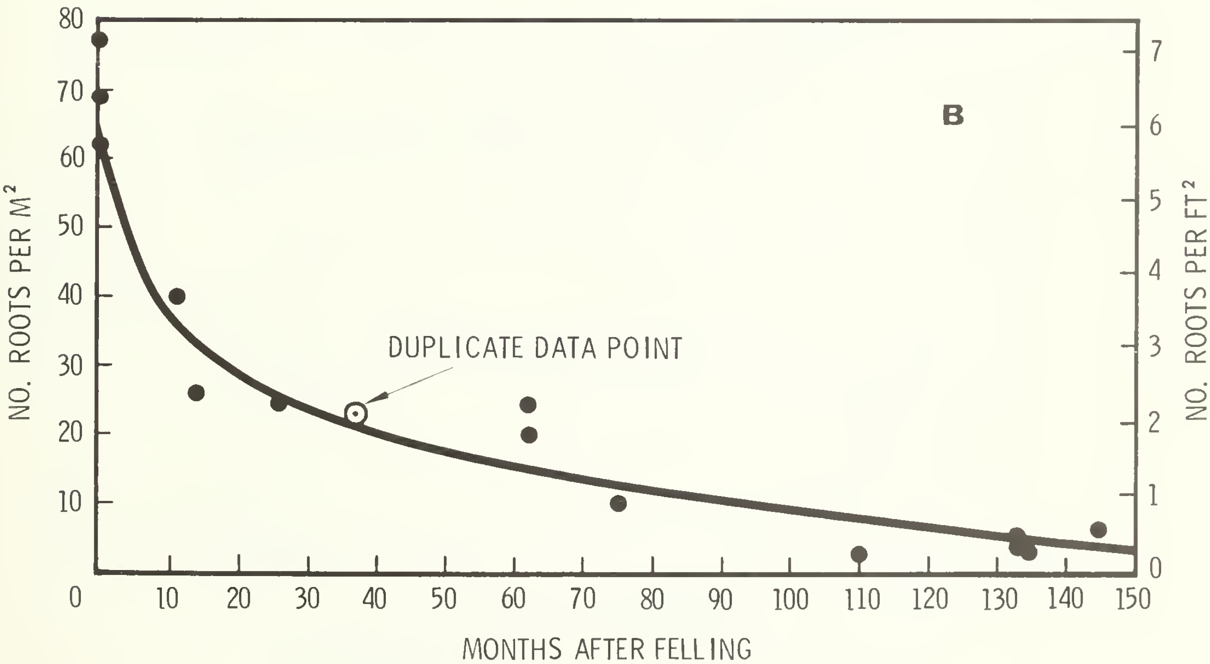


Figure 17.--Decline in numbers of Rocky Mountain Douglas-fir roots per unit area of soil: A, *Plot of raw data for the 0 to 1 cm (0 to 0.39 in) size class;* B, *Plot of raw data for the 0 to 4 mm (0 to 0.16 in) size class.*

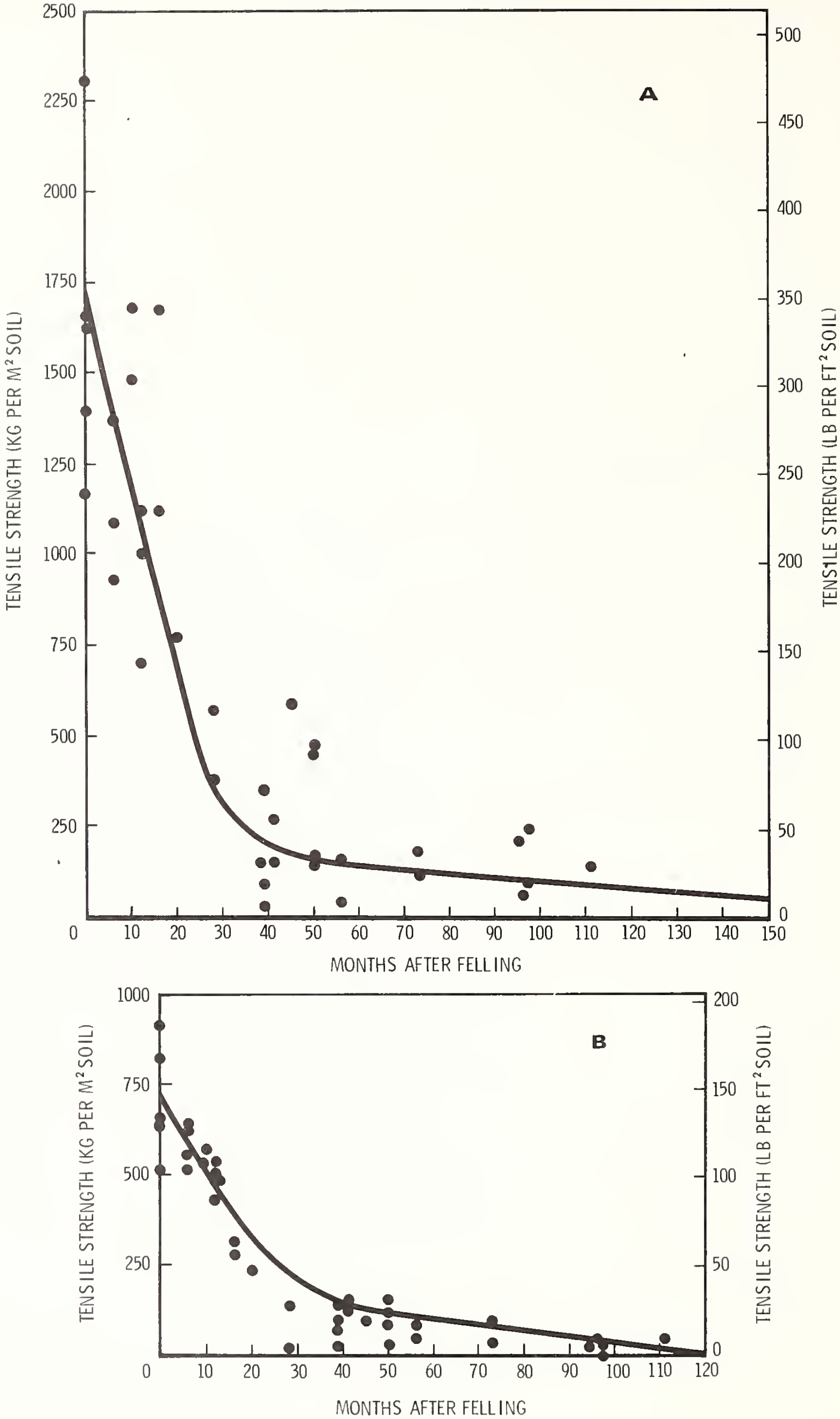


Figure 18.--Decline in tensile strength per unit area of soil for Coast Douglas-fir: A, *Plot of raw data for the 0 to 1 cm (0 to 0.39 in) size class;* B, *Plot of raw data for the 0 to 4 mm (0 to 0.16 in) size class.*

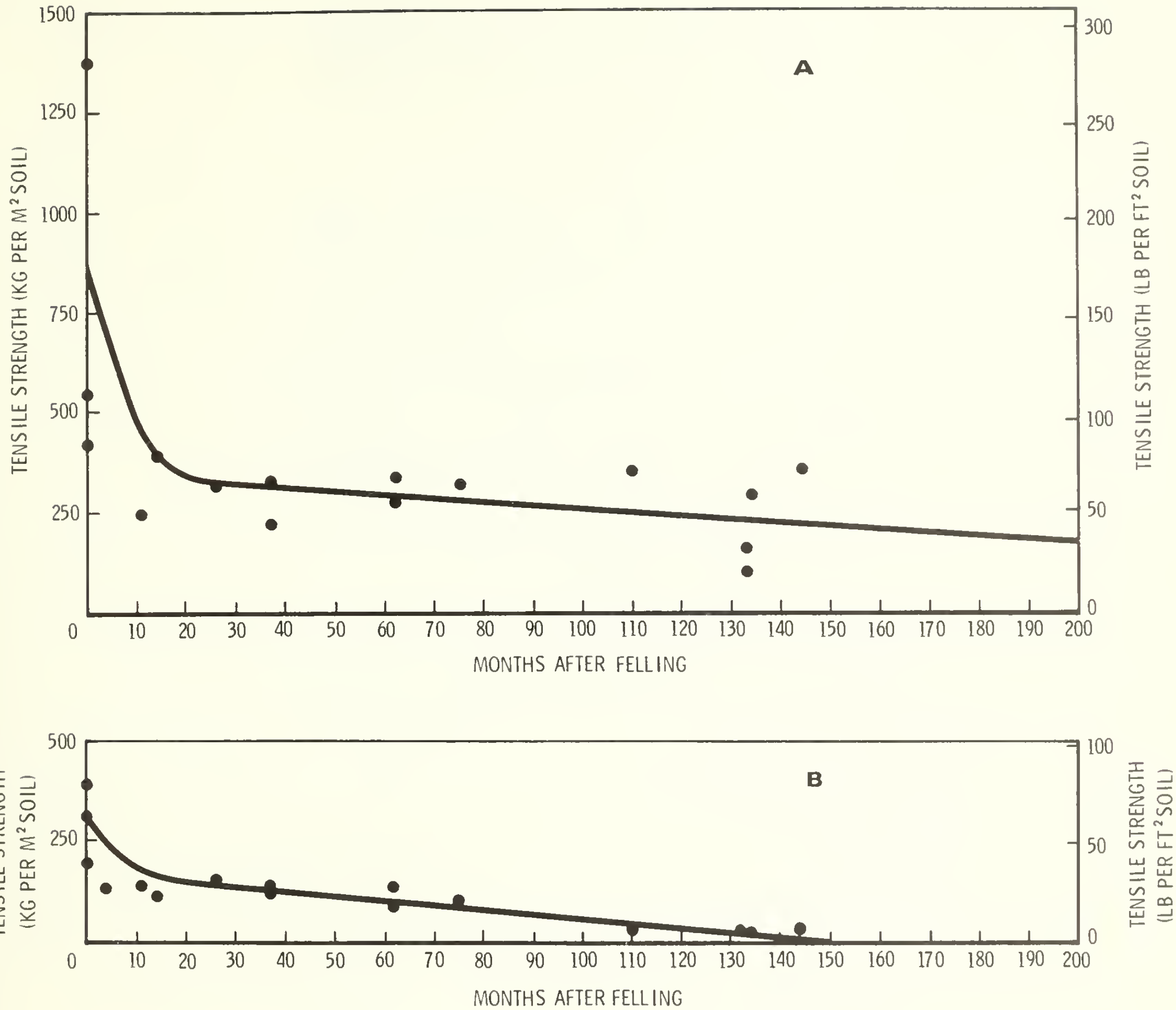


Figure 19.--Decline in tensile strength per unit area of soil for Rocky Mountain Douglas-fir: A, *Plot of raw data for the 0 to 1 cm (0 to 0.39 in) size class;* B, *Plot of raw data for the 0 to 4 mm (0 to 0.16 in) size class.*

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Burroughs, Edward R., Jr., and Byron R. Thomas
1977. Declining root strength in Douglas-fir after felling as a factor in slope stability. USDA For. Serv. Res. Pap. INT-190, 27 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

Numbers of roots per unit area of soil and tensile strength of individual roots declined with time after felling in both Coast and Rocky Mountain varieties of Douglas-fir. Reduction in numbers of roots and root tensile strength were combined to estimate total tensile strength per unit area of soil. Within 30 months after felling, Coast Douglas-fir lost 86 percent of its total root tensile strength (kg m^2), and Rocky Mountain Douglas-fir lost 65 percent of its strength. Coast Douglas-fir roots are about twice as strong as Rocky Mountain fir roots when live, but decay at a faster rate following felling.

KEYWORDS: tree roots, root systems, Coast Douglas-fir, Rocky Mountain Douglas-fir, slope stability

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